

Oxygen Consumption by Portal Vein-Drained Organs and by Whole Animal in Conscious Growing Swine (42878)

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Abstract. A method was developed to measure simultaneously the $\dot{V}O_2$ consumption ($\dot{V}O$) by the whole animal and by the hepatic portal vein-drained organs (PVDO), including the gastrointestinal tract, spleen, and pancreas in conscious 3.5- to 4-month-old swine. The method was used to determine (i) the effect of feeding on hepatic portal vein blood flow rate (\dot{Q}_{pv}) and $\dot{V}O$ by PVDO and by the whole animal, and (ii) the significance of PVDO on the oxidative demand in the pig. Chronic cannulas were placed in the hepatic portal vein, carotid artery, and ileal vein. The \dot{Q}_{pv} was determined by an indicator dilution technique employing continuous constant infusion of 1% *p*-aminohippuric acid into the ileal vein. The $\dot{V}O_2$ by PVDO was estimated by multiplying \dot{Q}_{pv} by arterial-portal vein O_2 difference measured with an arterial-venous O_2 difference analyzer connected to the carotid artery and portal vein cannulas. Whole animal $\dot{V}O_2$ was measured with an open circuit indirect calorimeter. In seven pigs (3.5- to 4-month-old, 37.4 ± 0.8 kg) trained to be fed once daily, feeding (1.2 kg of feed mixed with 1.2 liter of H_2O) caused postprandial (6 hr) \dot{Q}_{pv} to increase more than $34 \pm 15\%$ above the preprandial value of 34.5 ± 4.2 $ml \cdot min^{-1} \cdot kg^{-1}$ body wt. The postprandial $\dot{V}O_2$ by PVDO was elevated more than $46 \pm 12\%$ above the value of 1.52 ± 0.20 $ml \cdot min^{-1} \cdot kg^{-1}$ body wt observed during the preprandial period. Whole animal $\dot{V}O_2$ increased 45 ± 9 and $33 \pm 7\%$ above the preprandial value of 6.23 ± 0.57 $ml \cdot min^{-1} \cdot kg^{-1}$ body wt for the first 6 hr and the 7 to 12 hr after feeding, respectively. Although PVDO represent only 5% of body weight, they used 25% of whole body $\dot{V}O_2$. The study clearly illustrates the significance of PVDO on the whole animal oxidative demand in conscious growing swine. [P.S.E.B.M. 1989, Vol 190]

Using a common umbilical vein catheter to gain access to the hepatic portal vein, Nowicki *et al.* (1) were able to make acute measurements of portal vein oxygen content in awake newborn pigs. The oxygen consumption ($\dot{V}O$) by the gastrointestinal tract in those pigs was then derived by multiplying the arterial-portal vein oxygen content difference by the GI tract blood flow estimated by radiolabeled microsphere technique. A postprandial hyperemia and enhanced $\dot{V}O$ was found to occur in the GI tract of those newborn pigs in response to feeding. Little is known about the effect of feeding on the circulatory response and $\dot{V}O$ in the GI tract and related organs of the older and more matured pigs. Recently, we described a technique for chronically cannulating the hepatic portal vein, ileal

vein, and systemic artery such as carotid artery in 3-month-old growing pigs (2). Because the hepatic portal vein collects blood from the GI tract, pancreas, and spleen (3), the technique provides a means to measure chronically hepatic portal vein blood flow rate (\dot{Q}_{pv}) and $\dot{V}O$ by the hepatic portal vein-drained organs (PVDO), including the GI tract, pancreas, and spleen in the pigs.

In this study, we report a method to measure simultaneously $\dot{V}O_2$ by PVDO and by the whole animal in conscious 3.5- to 4-month-old growing pigs. The method was used to investigate the effect of feeding on \dot{Q}_{pv} and $\dot{V}O_2$ by PVDO and by the whole animal and to determine the significance of PVDO on the oxidative demand by whole animal in 3.5- to 4-month-old pigs. In cattle, PVDO account for 18 to 25% of whole animal $\dot{V}O_2$ but only 8–10% of whole animal body weight (4).

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Materials and Methods

Animals. Seven crossbred (Chester White \times Landrace \times Large White \times Yorkshire) female 9- to 10-

week-old pigs weighing 22.0 ± 0.8 kg initially were trained to be housed individually in a temperature-controlled room (21°C) and fed once daily at 0930 hr a 16% crude protein corn-soybean meal diet (5, 6) at an amount of 1.2 kg mixed with 1.2 liter of H_2O .

Surgical Techniques. When the pigs weighed 33.4 ± 0.8 kg, chronic cannulas were surgically placed in the hepatic portal vein, carotid artery, and ileal vein. Pigs were fasted for 24 hr and anesthetized by injection of a 2.5% solution of sodium thiopental, with a dosage of 0.5–0.75 ml/kg, into the cranial vena cava. One ear vein of the pig was then cannulated. The pig was then prepared for operation and placed under closed circuit anesthesia via a face mask. The anesthesia was maintained with 1–2% of vaporized halothane and 2000 ml/min of oxygen. A lactated Ringer solution with 5% dextrose was infused ($10 \text{ ml} \cdot \text{hr}^{-1} \cdot \text{kg}^{-1}$) continuously through the ear vein cannula during the surgery.

Through an incision caudal and parallel to the last rib on the right side of the animal, a polyurethane (Micro-Renathane, Braintree Scientific, Inc., Braintree, MA) tubing (1.68 mm inside diameter, 2.41 mm outside diameter) was inserted into the hepatic portal vein and another (0.65 mm inside diameter, 1.02 mm outside diameter) was placed in the ileal vein. The lumen of the tubing had been treated previously with a heparin complex (TDMAC-heparin complex; Polysciences, Inc., Warrington, PA) to prevent blood clotting. After exteriorizing the portal vein and ileal vein cannulas from the abdominal cavity, the incision was closed. The pig was then placed in dorsal recumbency. A ventral midline incision was made over the larynx and the right carotid artery was cannulated with a tubing having the same inside diameter and outside diameter as the portal vein cannula. The carotid artery cannula was exteriorized to the base of the right ear.

The distal end of the portal vein, ileal vein, and carotid artery cannulas were further exteriorized through subcutaneous tunnels and exited at the dorsal midline. They were anchored to the skin by collars made by Silastic tubing. The lumens of the cannulas were filled with heparinized saline solution (200 units/ml) and capped. A nonirritating iodine complex solution containing 1% titratable iodine was applied to the wound. No medication was given to the animal during the recovery period.

The animal was considered to be fully recovered when its appetite returned to the preoperative level. It took 4.7 ± 1.1 days for the appetite to recover. The cannulas were checked for their patency, flushed, and refilled with heparinized saline every 1 to 2 days. Detailed surgical procedures and construction of the cannulas have been described previously (2).

Measurements of \dot{Q}_{pv} and $\dot{V}\text{O}_2$ by PVDO and Whole Animal. After the pig had resumed its preoperative appetite for at least 6 days, the animal was weighed 5 hr postprandially at 1430 hr and placed into an open

circuit indirect calorimeter (7). The seven pigs used for the measurements weighed 37.4 ± 0.8 kg and were 3.5 to 4 months of age. On the following day at 0730 hr, the Plexiglas door of the calorimeter was opened. The ileal vein cannula was connected to a 2-m Tygon microbore tubing (0.75 mm inside diameter, 2.29 mm outside diameter) which entered the calorimeter through a sealed rubber stopper. The distal end of the Tygon tubing was then connected to a sterile disposable 25-mm filter assembly containing a polysulfonate membrane with 0.2- μm pore size (Acrodisc; Gelman Sciences Inc., Ann Arbor, MI). A 0.9% saline solution containing 1% of *p*-aminohippuric acid (PAH) with pH = 7.45 was infused continuously through the filter assembly into the ileal vein with a syringe pump (Harvard infusion-withdraw pump, series 940; Harvard Apparatus Co., Inc., Millis, MA) at a rate of 3.82 ml/min for 5 min to prime the pig. After priming, the infusion rate was changed to 0.788 ml/min.

The portal vein and carotid artery cannulas each were connected to a 1.2-m TDMAC-heparin complex-treated Micro-Renathane tubing which entered the calorimeter through the same sealed rubber stopper used for the ileal vein cannula. The distal end of the tubes were then connected to a Gilson Minipuls 2 (HP4) peristaltic pump (Gilson Medical Electronics, Middleton, WI) and led to the optical cuvettes of an arterial-venous O_2 difference analyzer (Avox Systems, Inc., San Antonio, TX). Each outlet of the arterial and venous cuvettes was fitted with a three-way stopcock for blood sampling and for flushing the tubing and optical cuvette. Figure 1 diagrams the system for the whole body calorimetry and the \dot{Q}_{pv} and $\dot{V}\text{O}_2$ measurements of conscious swine.

The Avox analyzer was calibrated daily by first clamping the portal vein blood sampling line at point X^1 as shown in Figure 1, and then opening the shunt between the portal and arterial sampling lines (X^2 in Fig. 1) to perfuse both cuvettes of the Avox analyzer with arterial blood at a rate of 8.3 ml/min. The accuracy and reliability of the Avox analyzer for analyzing O_2 difference in whole blood has been established by Shepherd and Burgar (8). Longo *et al.* (9) reported the reproducibility of the Avox system for O_2 analysis was $\pm 5\%$ and the correlation coefficient between Avox and Lex- O_2 -Con (Lexington Instruments, Waltham, MA) measurements was 0.99 in the studies with ewes.

At 0800 hr the door of the calorimeter was closed and the calorimetry system was allowed to equilibrate for 60 min before gaseous measurements were taken. The intake and exhaust air from the calorimeter were sampled at 5-min intervals and analyzed automatically with a paramagnetic O_2 analyzer (model 755; Beckman Instruments, Inc., Fullerton, CA) to determine the average 5-min $\dot{V}\text{O}_2$ of the whole animal. The design and operation of our calorimeters have been reported previously (7). The gaseous measurements for the whole

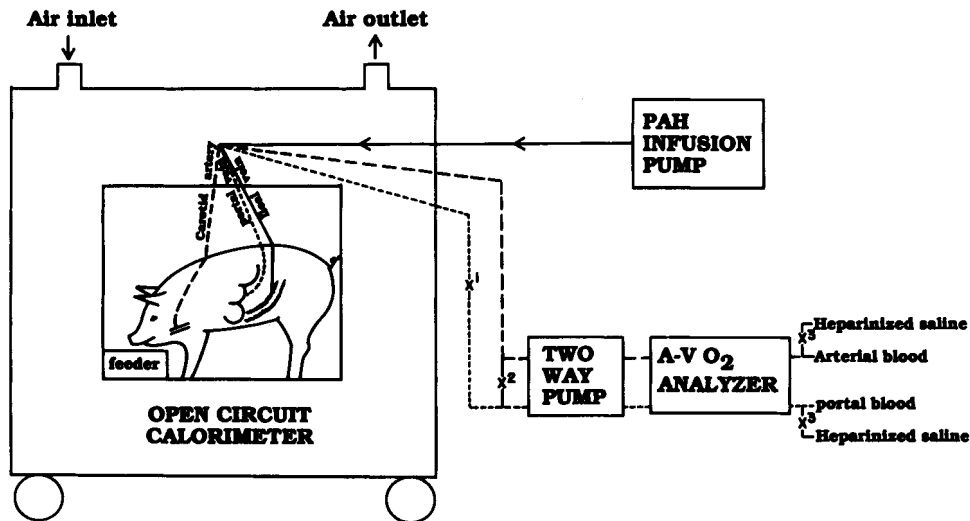


Figure 1. Diagram of system for measuring simultaneously O_2 consumption by whole animal and hepatic portal vein-drained organs in conscious swine.

animal were conducted from 0.5 hr preprandially to 12 hr postprandially. The premeasured feed (1.2 kg) and water (1.2 liter) were stored inside the upper compartment of the calorimeter. The feed and water were delivered to the feeder at 0930 hr by the use of a plastic glove that was attached and sealed to the upper compartment of the calorimeter. The 5-min interval measurements of O_2 were corrected to standard temperature and pressure. The 5-min values were pooled to derive the hourly average $\dot{V}O_2$ for the 0.5-hr preprandial and 12-hr postprandial periods. The accuracy of the $\dot{V}O_2$ measurement of the calorimeter was $100.9 \pm 0.3\%$ (7).

Prior to feeding, the O_2 difference between carotid artery and hepatic portal vein ($CaO_2 - Cp_vO_2$) of the pig was measured by activating the peristaltic pump to perfuse the optical cuvettes of the Avox analyzer. After the O_2 difference reading was taken, two syringes containing lithium-heparin were each connected to the three-way stopcock (X^3 of Fig. 1) on the outlet line from the carotid artery or hepatic portal vein for blood sampling. After the syringes were filled with approximately 8 ml of blood, the peristaltic pump was stopped, the direction of flow through the three-way stopcock was switched, and the pump was activated in the reverse direction to withdraw heparinized saline from the 20-ml syringes connected to the three-way stopcock. After 18 ml of heparinized saline were withdrawn each from the syringes, the peristaltic pump was stopped. Thus, the optical cuvettes, tubings, and cannulas were completely flushed and refilled with heparinized saline.

The portal and arterial blood samples were stored on ice. The packed cell volume (PCV) of each sample was measured. Within 15 min after being collected, the blood was centrifuged at $4^\circ C$ and $3300g$ for 10 min to separate plasma from cells. Plasma was refrigerated and assayed within 12 hr for PAH concentration, by use of an automated procedure (Technicon Auto Analyzer II;

Technicon Instruments Corp., Tarrytown, NY) described by Harvey and Brothers (10).

The \dot{Q}_{pv} was estimated as described previously (2) by the indicator dilution technique, employing PAH as the indicator (11, 12) and with the following equation:

$$\dot{Q}_{pv} = C_i \times \dot{R} \times [C_{pvPAH} \times (100 - PCV_{pv}) \times 10^{-2} - C_{aPAH} \times (100 - PCV_a) \times 10^{-2}]^{-1}$$

where C_i is the concentration of PAH infusion solution (mg/ml), \dot{R} is infusion rate (ml/min), C_{pvPAH} is portal plasma PAH concentration (mg/ml), PCV_{pv} is portal blood PCV (%), C_{aPAH} is arterial plasma PAH concentration (mg/ml), and PCV_a is arterial blood PVC (%).

The $\dot{V}O_2$ by PVDO was calculated by multiplying \dot{Q}_{pv} by O_2 difference between carotid artery and portal vein blood ($CaO_2 - Cp_vO_2$).

Following the measurements, the pigs were removed from the calorimeter, returned to their individual pens, and fed once daily 1.2 kg of feed for 7 more days. They were weighed (final weight 41.9 ± 2.5 kg) and sacrificed 2 hr postprandially. Confirmation of correct cannula placement was conducted in every pig at necropsy. The entry of the cannula into the hepatic portal vein, ileal vein, or carotid artery was located. The proper placement of the cannula was evaluated first by palpating the blood vessel to locate the position and the tip of the cannula inside the blood vessel. It was further verified by cutting open the blood vessel for visual inspection of the cannula. Then, the gastrointestinal tract, spleen, and pancreas were removed for weight measurements. Stomach, cecum, and colon plus rectum were opened, rinsed in tap water to remove the contents, blotted dry, and weighed. Small intestine contents were removed by stripping manually and the empty small intestine was then weighed.

Data were subjected to a one-way analysis of vari-

ance using the General Linear Models procedure of SAS (13). A two-tailed Student's *t* test was used to compare least-squares means for time effect related to feeding.

Results and Discussion

Compared with the preprandial value (0 hr), the PCV value was significantly ($P < 0.05$) higher at 1 hr after feeding, but was significantly lower ($P < 0.05$) from 8 to 12 hr postprandially (Fig. 2). The higher PCV value at 1 hr after feeding probably was caused by the excitement associated with the feeding activity. Epinephrine released during excitement causes splenic contraction and the release of erythrocytes concentrated in the spleen (14). With the method described in the present study, approximately 30 ml of blood were removed from the pig at each sampling time. Although heparinized saline solution was infused into the animal after each sampling, no erythrocytes were infused back to the animal. This may explain lower PCV values observed in the pigs from 8 hr after feeding.

A constant arterial plasma PAH concentration during the entire 12-hr test period was observed in the present study and is in agreement with our previous report (2). This suggests that the kidneys were able to clear and stabilize the recirculating PAH and establish an equilibration of PAH within the body (15). Thus, the PAH infusion technique is applicable for pigs as well as for sheep (11, 12), or dogs (11) for estimating blood flow rate on the basis of Fick principle indicator dilution technique.

When expressed on per kg body weight basis, the

preprandial \dot{Q}_{pv} for the 3.5- to 4-month-old pigs used in this study was $34.5 \pm 4.2 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg body wt}^{-1}$ (Fig. 3) and was similar to our previously reported (2) value ($32.5 \pm 0.9 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg body wt}^{-1}$ in pigs weighing between 33 and 42 kg) and comparable to that determined with the electromagnetic probe method (16). In the studies with newborn pigs, the preprandial blood flow rate of the GI tract alone (\dot{Q}_{GI}) was found to be $106 \pm 9 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g tissue}^{-1}$ (1) or $43.8 \pm 2.2 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg body wt}^{-1}$ (P. T. Nowicki, personal communication). Because our \dot{Q}_{pv} includes not only the GI tract, but also spleen and pancreas, it seems inappropriate to compare the reported \dot{Q}_{GI} value for the newborn pigs with our \dot{Q}_{pv} value for the older pigs. Furthermore, comparison of our preprandial data with those in newborn pigs is limited to a significant degree by expression of these data per kg of body weight. Although a legitimate and useful method of data expression, this approach falls short herein because the relationship between the organ mass and body mass are not clearly established for both age groups. Although we present data to this effect for our animals in Table I, no such data are available for the newborn swine. Nonetheless, with *in vitro* ileal loops from 3- and 35-day-old swine, Nowicki and Miller (17) recently reported a higher blood flow in the 3-day-old pigs.

In this study with 3.5- to 4-month-old pigs eating their daily 1.2 kg of feed mixed with 1.2 liter of H_2O voluntarily, the \dot{Q}_{pv} was elevated by $38 \pm 2\%$ at 1 hr after feeding. The hyperemia persisted for the entire 12-hr postprandial period and was more than $34 \pm 15\%$ above the preprandial level during the first 6 hr and again at 9 hr postprandially. In neonatal pigs gavage of 30 ml/kg of artificial pig milk produced a $35 \pm 3\%$ increase in \dot{Q}_{GI} 30 min after feeding, and declining thereafter at 60 and 120 min postprandially (1). It is not clear why our pigs exhibited such a long postprandial hyperemia as compared with the neonatal pigs. Besides age, there were differences in training regimen and the amount and type of feed offered to the neonate and our older animals. Our pigs were trained to be fed only once every 24 hr, whereas the neonates were gavaged once every 3 hr. At each meal our pigs consumed 1.2 kg of dry feed plus 1.2 liter of H_2O , which is equivalent to 6.4% of the body weight, and the neonatal pigs were fed artificial pig milk at an amount equal to 3% of body weight. The nutrient composition of the artificial milk is also different from that of the 16% protein corn-soybean meal diet used for our pigs. A sustained presence of nutrients and digested products in the intestinal lumen might occur in our pigs. This could result in a prolonged hyperemia, because postprandial intestinal hyperemia is a locally mediated vascular response to the presence of nutrients in the lumen (18).

The preprandial \dot{V}_{O_2} by PVDO in the 3.5- to 4-month-old pigs in the present study was 1.52 ± 0.20

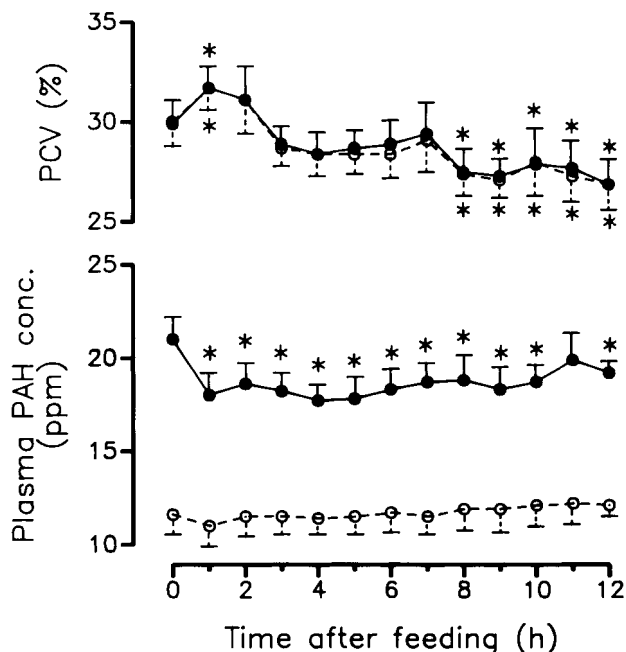


Figure 2. PCV and plasma PAH concentration of arterial (---) and hepatic portal vein (—) blood in 3.5- to 4-month-old pigs. Values are means \pm SE for seven pigs weighing $37.4 \pm 0.8 \text{ kg}$. * $P < 0.05$ when compared with 0-hr preprandial value.

Table I. Whole Animal Body Weight, Weights of Hepatic PVDO, and Ratio of PVDO to Weight in 3.5- to 4-month-old Growing Pigs^a

Variable	Means ± SE
Weight (kg)	41.886 ± 2.455
Stomach (kg)	0.363 ± 0.012
Small intestine (kg)	0.857 ± 0.023
Cecum (kg)	0.076 ± 0.008
Colon-rectum (kg)	0.585 ± 0.039
Pancreas (kg)	0.069 ± 0.003
Spleen (kg)	0.080 ± 0.007
PVDO (kg)	2.030 ± 0.067
PVDO/weight (%)	4.9 ± 0.2

^a Values are means ± SE of seven female (Chester White × Landrace × Large White × Yorkshire) crossbred pigs.

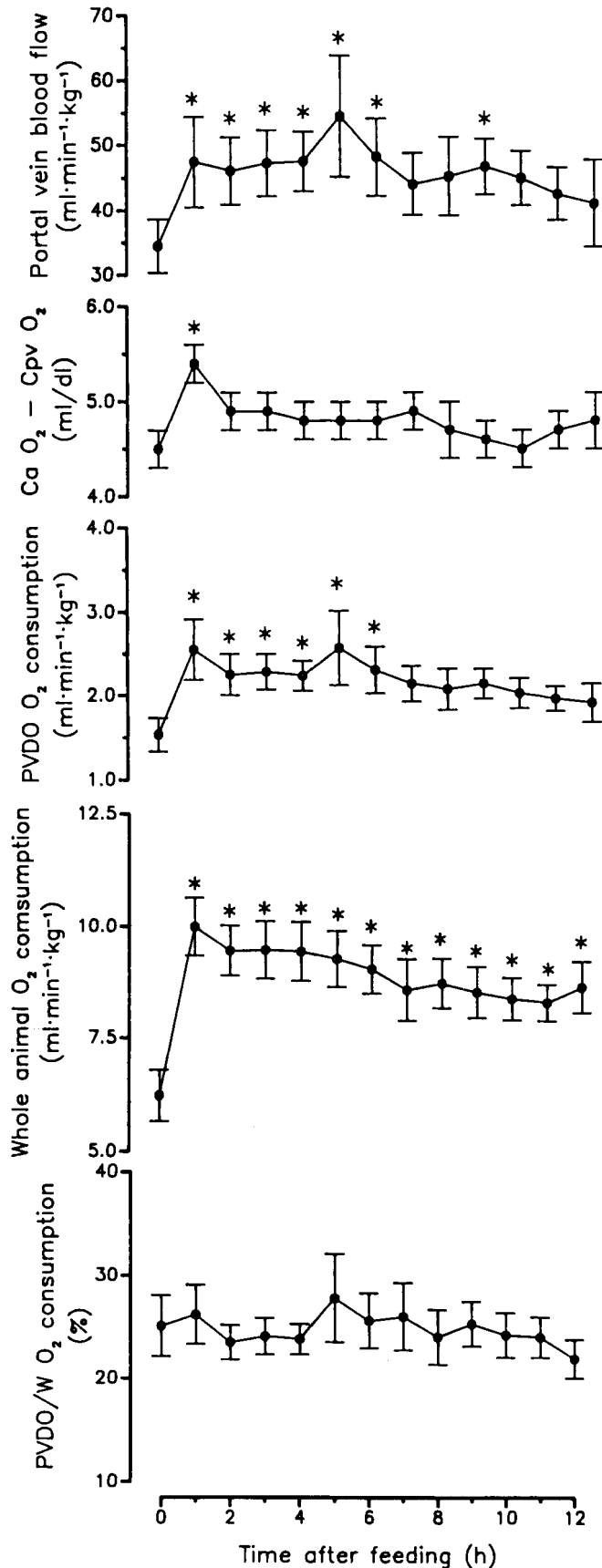


Figure 3. Effect of feeding on hepatic portal vein blood flow rate, oxygen difference between carotid artery and hepatic portal vein ($\text{CaO}_2 - \text{CpVO}_2$), O_2 consumption by hepatic PVDO, whole animal O_2 consumption, and percentage of O_2 consumption by hepatic PVDO as related to whole animal (W) in 3.5- to 4-month-old pigs. Values are

$\text{ml} \cdot \text{min}^{-1} \cdot \text{kg} \text{ body wt}^{-1}$ and in the newborn pigs, the preprandial $\dot{\text{V}}\text{O}_2$ by the GI tract was reported to be $0.77 \pm 0.07 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg} \text{ body wt}^{-1}$ or $1.99 \pm 0.19 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ g tissue}^{-1}$ (1). However, the significance of comparing our data with those in newborn swine may be limited as previously indicated in the comparison of preprandial blood flow rate. Nevertheless, in anesthetized pigs, the intestinal $\dot{\text{V}}\text{O}_2$ derived from superior mesenteric blood flow and arteriovenous O_2 difference was found to be higher in 1-day-old pigs than in 2-week-old pigs and 1-month-old pigs (19). However, no difference in $\dot{\text{V}}\text{O}_2$ was observed in *in vitro* ileal loops between 3-day-old and 35-day-old pigs (17).

In this study, postprandial $\dot{\text{V}}\text{O}_2$ by PVDO of 3.5- to 4-month-old pigs during the first 6 hr after feeding was increased more than $46 \pm 12\%$ above the preprandial value. This increase was due to the elevation of $\dot{\text{Q}}_{\text{pv}}$, because $\text{CaO}_2 - \text{CpVO}_2$ did not change during the 12-hr postprandial period, with the exception at 1 hr after feeding when $\text{CaO}_2 - \text{CpVO}_2$ was increased by $20 \pm 4\%$. In newborn pigs, $\dot{\text{V}}\text{O}_2$ by GI tract increased by $72 \pm 5\%$ at 30 min postprandially, declining toward preprandial values at 60 to 120 min after feeding (1).

As shown in this study, whole animal $\dot{\text{V}}\text{O}_2$ in 3.5- to 4-month-old pigs was $6.23 \pm 0.59 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg} \text{ body wt}^{-1}$ during the preprandial period. It was increased more than 45 ± 9 and $33 \pm 7\%$, respectively, for the first 6 hr and 7- to 12-hr postprandial periods. In the study with neonatal pigs, no measurements were conducted on whole animal $\dot{\text{V}}\text{O}_2$. Thus, no comparison of whole animal $\dot{\text{V}}\text{O}_2$ can be made between the neonatal and our older pigs.

The percentage of the whole animal $\dot{\text{V}}\text{O}_2$ used by PVDO in 3.5- to 4-month-old pigs, as observed in this study, was not changed significantly ($P > 0.05$) by feeding and averaged $24.8 \pm 0.7\%$. As shown in Table I, the combined PVDO weighed $2.03 \pm 0.067 \text{ kg}$ for

means ± SE for seven pigs. * $P < 0.05$ when compared with 0-hr preprandial value.

pigs weighing 41.886 ± 2.455 kg at necropsy. The PVDO, thus, only represented $4.9 \pm 0.2\%$ of whole animal body weight, even though it used $24.8 \pm 0.7\%$ of the whole animal $\dot{V}O_2$. This disproportionately high $\dot{V}O_2$ by PVDO in 3.5- to 4-month-old pigs clearly illustrates the significance of PVDO in the whole animal oxidative demand and their importance in whole animal energetics. In cattle, PVDO has been shown to account for 8 to 10% of body weight but 18 to 25% of whole animal O_2 consumption (4).

Feeding causes a 6-hr prolonged hyperemia and enhanced O_2 consumption in hepatic portal vein-drained organs, including gastrointestinal tract, spleen, and pancreas, of 3.5- to 4-month-old pigs weighing 37.4 ± 0.8 kg and fed once daily. Although hepatic portal vein-drained organs represent only a small portion (4.9%) of body weight, they use a disproportionately high amount (24.8%) of whole body O_2 consumption.

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